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Capillary Discharge Thruster Experiments and Modeling

Robert Martin[1]

ERC Inc.[1], In-Space Propulsion Branch,
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Edwards Air Force Base, CA USA

Electric propulsion systems
June 2016, Rhode-Saint-Genèse, Belgium

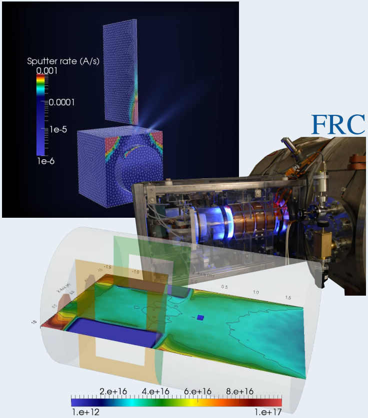
Outline

Spacecraft Propulsion Relevant Plasma:

- From hall thrusters to plumes and fluxes on components
- Complex reaction physics i.e. Discharge and Breakdown in FRC
- Relevant Densities often Span 6+ Orders of Magnitude
- Spatial scales of interest span μm-100m range

Electric Propulsion Plumes

FRC



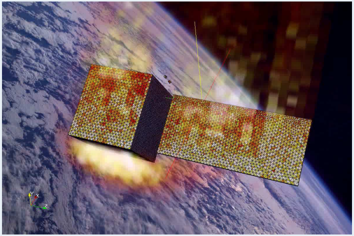
Chamber Environment

Spacecraft Propulsion Relevant Plasma:

- From hall thrusters to plumes and fluxes on components
- Complex reaction physics i.e. Discharge and Breakdown in FRC
- Relevant Densities often Span 6+ Orders of Magnitude
- Spatial scales of interest span μm-100m range

All Relatively Low Energy Density...
Connection to HEDP Capillary Discharge?

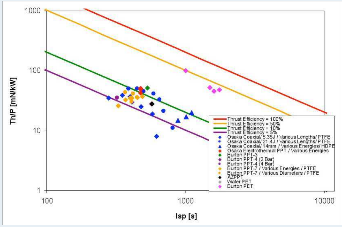
All Rarefied Gas and Plasma



...and Highly Non-Equilibrium

Need Efficiency Across Thrust Range:

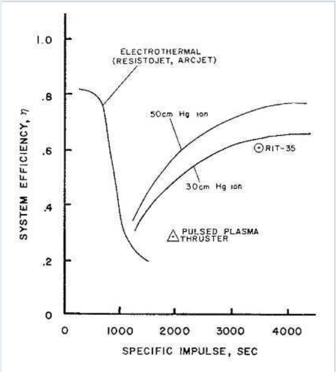
- Spacecraft Power is Constrained
- Fundamental Tradeoff: Isp vs. Thrust
- Optimal Trade Mission Dependent (i.e. Station Keeping vs. Orbit Insertion)



Pancotti, PhD Dissertation, USC, 2009.

Need Efficiency Across Thrust Range:

- Spacecraft Power is Constrained
- Fundamental Tradeoff: Isp vs. Thrust
- Optimal Trade Mission Dependent (i.e. Station Keeping vs. Orbit Insertion)
- Electrothermal - Electrostatic Gap

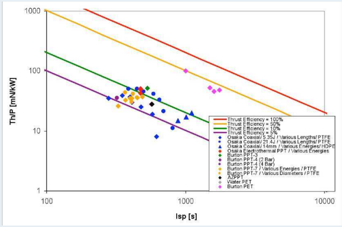


Burton, et. al., AIAA Paper, (TDS83-10), 1983.

Need Efficiency Across Thrust Range:

- Spacecraft Power is Constrained
- Fundamental Tradeoff: Isp vs. Thrust
- Optimal Trade Mission Dependent (i.e. Station Keeping vs. Orbit Insertion)
- Electrothermal - Electrostatic Gap
- Burton Predicted[1]/Demonstrated[2] Efficient Pulsed Electrothermal (PET)

[1] Burton, Goldstein, Tidman, Winsor, AIAA Paper, 82(1952), 1982.
[2] Burton, Fleischer, Goldstein, Tidman, Winsor, NASA, (CR-179464), 1984.



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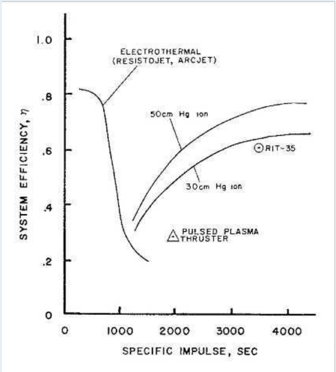
Capillary Discharge Thruster Viability:

- Efficiency Gap for Moderate ISP EP (750s-3000s)
- Capillary Discharge Conceptually Efficient (η_t>65%) in this Range
- Burton Predicted $\eta_t \approx 80\%$
- Burton Observed only 56% Max (0.085 Ns @ 1600s Isp)
- Realizing full Efficiency requires Deeper HED Physics Understanding
- CDTs are Simple Small Devices Accessible to Lab Experiments

Must Converge...

Theory, Models, and Experiments



Burton, et. al., AIAA Paper, (TDS83-10), 1983.

Key Processes for Design & Efficiency:

- Assumptions

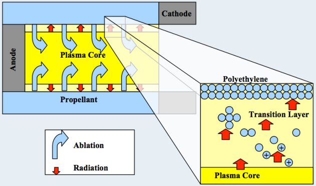
  -Unmagnetized/LTE/Coupling
- Energy Balance

  -Conduct/Evaporate/Bond Break/Ionize
- Ablation

  -Photo-ablation/Macro-particles/Pyrolysis
- Radiative Transport

  -Optical Depth/Spectrum
- Ionization/Recombination

  -Breakdown/Recombination Rate



Pancotti, PhD Dissertation, USC, 2009.

Key Processes for Design & Efficiency:

- Magnetization

  -Essentially Electrothermal

  -Weaker Assumption if $n=\mathcal{O}(1e24/m^3)$

Plasma-β:

$$\beta = \frac{P_T}{P_B}$$

$$P_T = nkT \;\&\; P_B = \frac{B^2}{2\mu_0}$$

$$B = \frac{\mu_0 I}{2\pi r}$$

$$\beta = \frac{8nkT}{\mu_0}\left(\frac{\pi r}{I}\right)^2$$

Using:

T=2eV, n=1e25/m^3, r=2mm, I=6kA

$\beta=22\gg1$

Key Processes for Design & Efficiency:

- Magnetization
- Local Thermodynamic Equilibrium

  -LTE: Acceleration/Collision Balance

  -Highly Collisional After Breakdown

LTE Parameter:

$$K = \frac{\Delta\epsilon_{e\leftrightarrow i}}{\Delta\epsilon_E}$$

$$\Delta\epsilon_{e<->i} = T\left(\frac{2m_e}{m_i}\right)$$

$$\Delta\epsilon_E = \frac{e^2}{m_e}\frac{E}{\nu_{ei}}$$

$$K = \frac{1}{128}\frac{e^6}{\pi^2\epsilon_0^4k^3}\frac{m_e}{m_i}\left(\frac{n}{ET}\right)^2$$

Using:

T=2eV, n=1e25/m^3, E=1e5V/m

$$K \approx 2.5e8$$

Key Processes for Design & Efficiency:

- Magnetization
- Local Thermodynamic Equilibrium
- Plasma Coupling
  - -Potential/Kinetic Energy Balance
  - -Degree Ideal Plasma EOS Applies

Non-Ideal Parameter:

$$\Gamma = \frac{U_{PE}}{U_{KE}}$$

$$U_{PE} = \frac{e^2}{4\pi\epsilon_0\bar{r}} = \frac{e^2 n^{1/3}}{4\pi\epsilon_0}$$
$$U_{KE} = kT$$

$$\Gamma = \frac{e^2 n^{1/3}}{4\pi\epsilon_0 kT}$$

Using:

T=2eV, n=1e25/m^3

$$\Gamma \approx 0.16$$

Non-Ideal? $\Gamma < 1$, but not $\Gamma \ll 1$?

Ideal Assumption Used, but Should be Revisited.

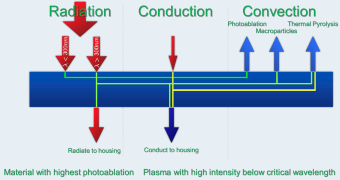
Key Processes for Design & Efficiency:

- Energy Balance

-Evaporate C_2H_4 fron wall:	0.5eV
-Break C-C Bond:	4.5ev
-Break 4 C-H Bond:	14.0eV
Total 6 Atoms:	19.0ev
-Dissociation Energy/Atom:	3.2eV
-Mean Ionization Energy/Atom:	12.8ev
Total Energy/Ion:	16.0ev

Would be Energy Sink Inhibiting Efficiency... but Recombination before Exit Captures Ion Energy!

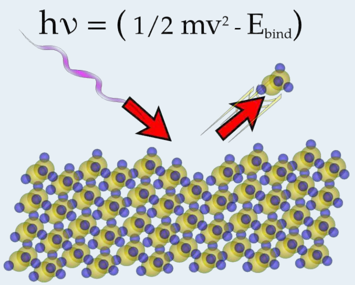
Losses via Radiation/Conduction to Housing... Limited on Discharge Timescales



Pancotti, PhD Dissertation, USC, 2009.

Key Processes for Design & Efficiency:

- Photo-Ablation
  -Direct Ablation by Photon Energy
  -Polymers Highly Susceptible to Photo-Ablation
  -Still Requires $\lesssim$300nm Photons



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  -Polymers Highly Susceptible to Photo-Ablation
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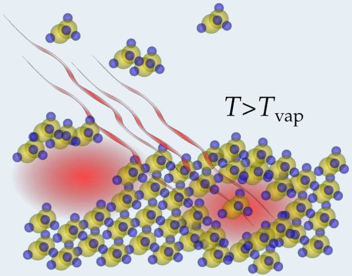
- Macro-Particles
  -Subsurface Energy Deposition
  -Vaporaztion Ejects Macro-particles
  -Particles Evaporate Quickly (S/V ratio)



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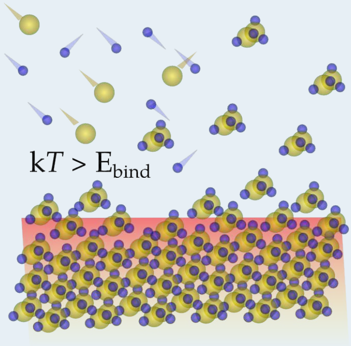
- Pyrolysis
  - -Thermal Evaporation
  - -Surface Temperature must Exceed T_{vap}
  - -Conductive Losses with T_{vap}



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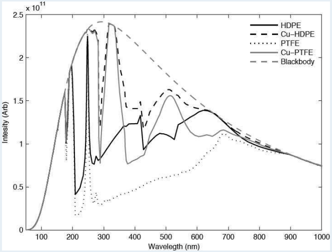
  -Conductive Losses with T_{vap}

Direct Ablation Preferable... Spectrum?

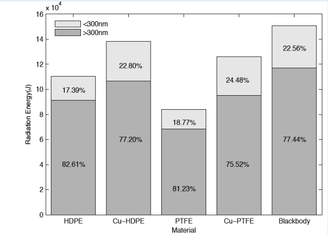
CD Process: Radiation

Key Processes for Design & Efficiency:

- Spectrum
  - -Several Materials Investigated
  - -Spectra Generated using PrismSpect®
- Optical Depth
  - $-\lambda_{mfp}^{rad} \approx \mathcal{O}(1)R - \mathcal{O}(0.1)R$
  - -High Radiation Conductivity $\rightarrow$ Uniform T



T=1.5ev, n=1.5e25 m^{-3}

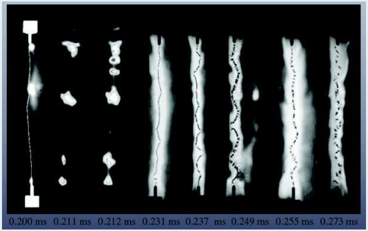


Pancotti, PhD Dissertation, USC, 2009.

Key Processes for Design & Efficiency:

- Ionization Process

  -Wire Breakdown is Chaotic



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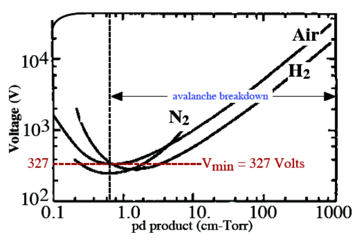
Key Processes for Design & Efficiency:

- Ionization Process
  - -Wire Breakdown is Chaotic
  - -Paschen Breakdown more Predictable
  - -Breakdown Voltage Density Dependent



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Key Processes for Design & Efficiency:

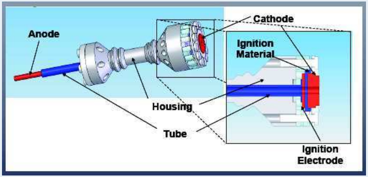
- Ionization Process

  -Wire Breakdown is Chaotic

  -Paschen Breakdown more Predictable

  -Breakdown Voltage Density Dependent

  -Spark



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Key Processes for Design & Efficiency:

- Ionization Process

  -Wire Breakdown is Chaotic

  -Paschen Breakdown more Predictable

  -Breakdown Voltage Density Dependent

  -Spark

- Recombination

  -Recombination Rate:

  $$\nu_e = \alpha_3 n^2 = 8.75 \times 10^{-27} T^{-9/2} n^2 \mathrm{Hz}$$

  (T in eV, n in cm$^-3$)

  -Thermal Velocity / Mean Free Path:

  $$u = \sqrt{\frac{8kT}{\pi \bar{m}}} \quad \lambda = \frac{u}{\nu_e}$$

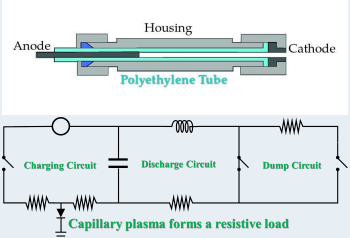
Device	Burton PET
Density, n^*	5.4e27/m^3
Temp, T^*	4ev
Rate, ν_e	5.0e14 Hz
Velocity, u^*	1.2e4 m/s
MFP, λ^*	2.4e-11 m

Device	Pancotti CDT(Est.)
Density, n^*	1.0e25/m^3
Temp, T^*	2ev
Rate, ν_e	3.9e10 Hz
Velocity, u^*	9.6e3 m/s
MFP, λ^*	2.5e-7 m

2.5e-7 m$\ll$2mm

Thruster Design & Ignition:

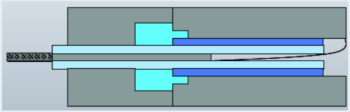
- Baseline



Pancotti, PhD Dissertation, USC, 2009.

Thruster Design & Ignition:

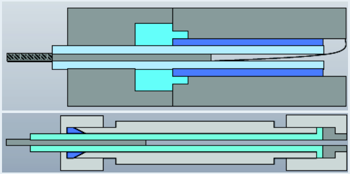
- Baseline
- Wire Ignition
  - Simple and Reliable
  - Chaotic Process
  - Random Ignition Delays
  - Bi-Modal Performance
  - Only Single Use



Pancotti, PhD Dissertation, USC, 2009.

Thruster Design & Ignition:

- Baseline
- Wire Ignition
  - Simple and Reliable
  - Chaotic Process
  - Random Ignition Delays
  - Bi-Modal Performance
  - Only Single Use
- Paschen Ignition
  - More Repeatable
  - Enabled Use of Thrust Stand
  - Requires some Background Density

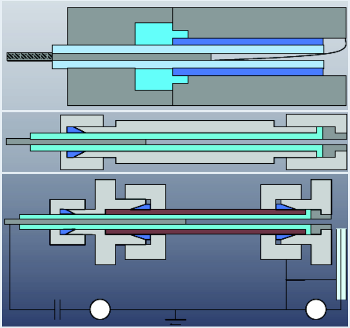


Pancotti, PhD Dissertation, USC, 2009.

Experimental Setup

Thruster Design & Ignition:

- Baseline
- Wire Ignition
  - Simple and Reliable
  - Chaotic Process
  - Random Ignition Delays
  - Bi-Modal Performance
  - Only Single Use
- Paschen Ignition
  - More Repeatable
  - Enabled Use of Thrust Stand
  - Requires some Background Density
- 3-Electrode Ignition
  - More Applicable to Space Vacuum
  - Dielectric Flashover
  - Less Electrode Erosion



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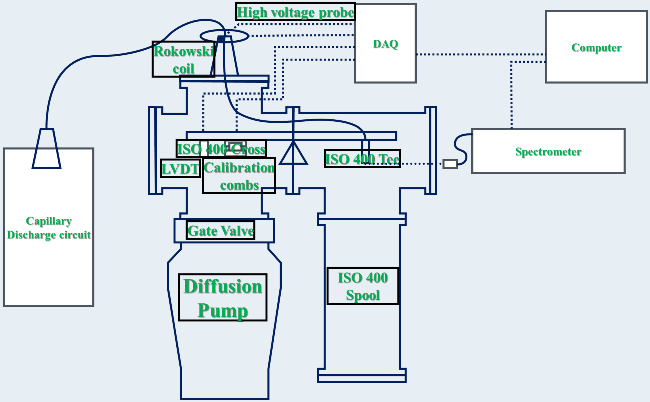

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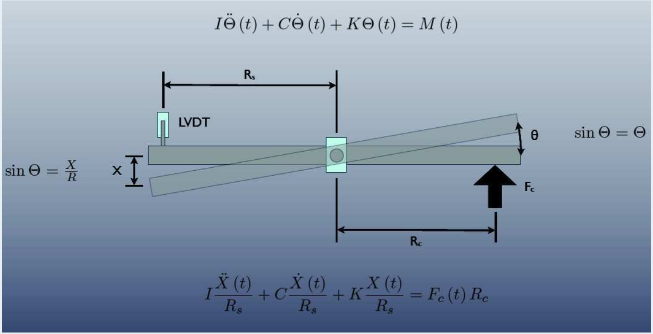

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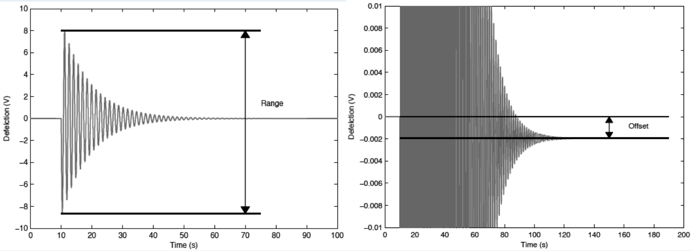

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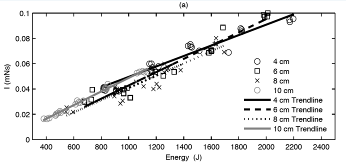
Key Processes for Design & Efficiency:

- Linear Impulse with Energy



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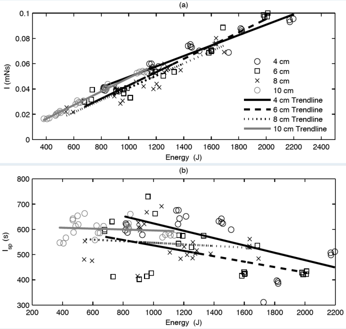
Key Processes for Design & Efficiency:

- Linear Impulse with Energy
- Large Scatter in Isp



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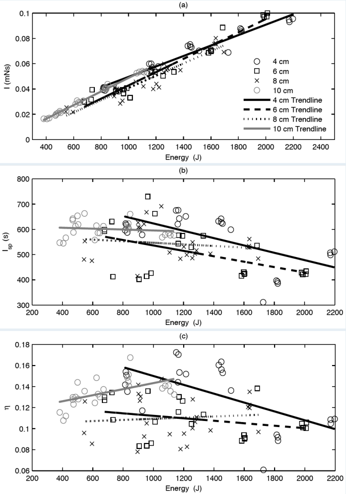
Key Processes for Design & Efficiency:

- Linear Impulse with Energy
- Large Scatter in Isp
- Large Scatter in Efficiency

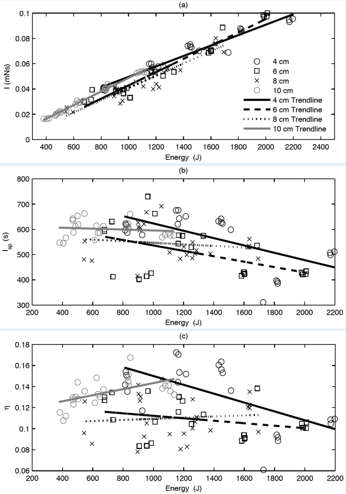


Pancotti, PhD Dissertation, USC, 2009.

Key Processes for Design & Efficiency:

- Linear Impulse with Energy
- Large Scatter in Isp
- Large Scatter in Efficiency
- Performace:
  - -Impulse: 20-100 mNs
  - -Specific Impulse: 350-700s
  - -Efficiency: 8-17% (Nozzleless Design)

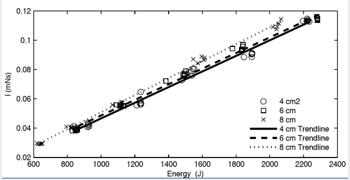
Scatter due to Electrode Erosion?



Pancotti, PhD Dissertation, USC, 2009.

Key Processes for Design & Efficiency:

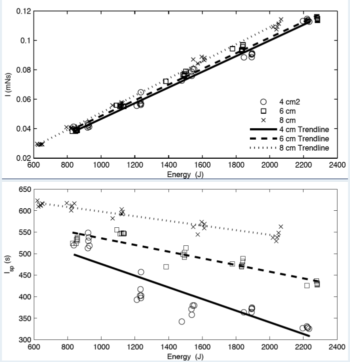
- Same Linear Impulse with Energy
- Better Correlated



Pancotti, PhD Dissertation, USC, 2009.

Key Processes for Design & Efficiency:

- Same Linear Impulse with Energy
- Better Correlated
- Clearer Isp Trends
- Higher Isp when Longer



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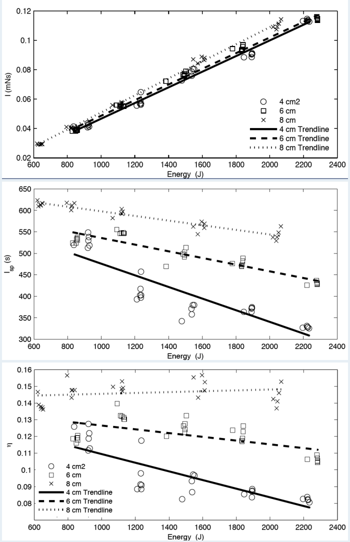
Key Processes for Design & Efficiency:

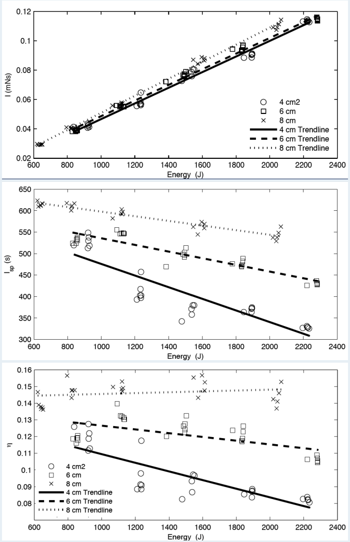
- Same Linear Impulse with Energy
- Better Correlated
- Clearer Isp Trends
- Higher Isp when Longer
- Longer also Higher Efficiency



Pancotti, PhD Dissertation, USC, 2009.

Key Processes for Design & Efficiency:

- Same Linear Impulse with Energy
- Better Correlated
- Clearer Isp Trends
- Higher Isp when Longer
- Longer also Higher Efficiency
- 8cm Efficiency Constant with Energy
- Performace:
  - -Impulse: 30-120 mNs
  - -Specific Impulse: 350-650s
  - -Efficiency: 9-17% (Nozzleless Design)

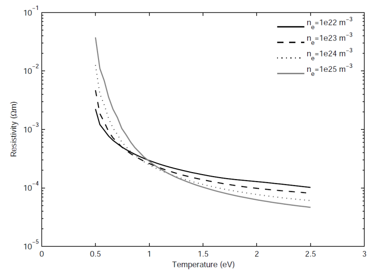


Pancotti, PhD Dissertation, USC, 2009.

Spitzer Resistivity:

- Ratio of Rate Electron Momentum Exchange to Current Density:
  $$\eta = 1/\sigma = \frac{P_{ei}}{j}$$
- For a Lorentz Gas:
  (Stationary Ions/Nonineracting Electrons)
  $$\eta_L = \frac{pi^{3/2} Z m_e^2 c^2 \nu ln\Lambda}{2(2kT)^{3/2}}$$
- With e-e Collsions (Spitzer-Härm)
  $$\eta = \frac{\eta_L}{\gamma_E}$$

Ionic Charge Z	1	2	4	16	∞
γ_E	0.582	0.683	0.785	0.923	1.000



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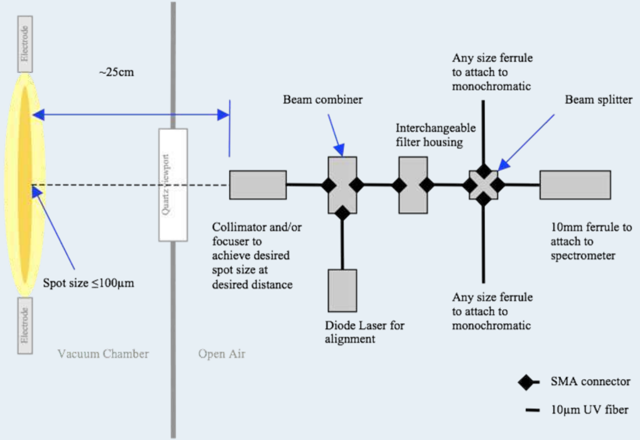
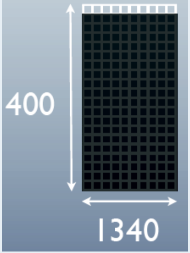
Optical Diagnostics



Pancotti, PhD Dissertation, USC, 2009.

Time Resolved OES:

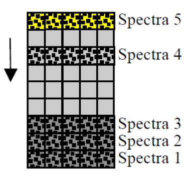
- Uses Spectral Line Shape not Intensity
  -Simpler Calibration
- Pulsed Device Requires Time Resolved
- Kinetics Mode via Pixel Time Shifts
  -5pixel/Spectra
  -16μs/Spectra
  -0.1nm/Pixel

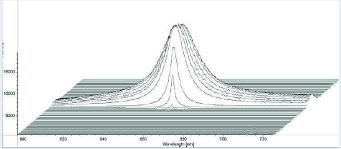


Pancotti, PhD Dissertation, USC, 2009.

Time Resolved OES:

- Uses Spectral Line Shape not Intensity
  -Simpler Calibration
- Pulsed Device Requires Time Resolved
- Kinetics Mode via Pixel Time Shifts
  -5pixel/Spectra
  -16μs/Spectra
  -0.1nm/Pixel





Pancotti, PhD Dissertation, USC, 2009.

Hydrogen-α Line Broadening:

- Neutral Broadening (Small)
- Doppler Broadening (H_α, H_β:<1Å)
- Resonance Broadening (N-N Collisions)
- Van der Waals Broadening (Also N-N Collisions)
- Stark Broadening $\mathcal{O}$(10nm)

$$\Delta^N_{1/2} \approx 1 \times 10^{-4}[\text{Å}]$$
$$\Delta^D_{1/2} = 7.16 \times 10^{-7}\lambda_0\sqrt{\frac{T}{M}}[\text{Å}]$$
$$\Delta^R_{1/2} = 8.6 \times 10^{-30}\sqrt{\frac{g_i}{g_k}}\lambda_0^2\lambda_r f_r N_i[\text{Å}]$$
$$\Delta^W_{1/2} \approx 3 \times 10^{-30}\lambda_0^2 C_6^{2/5}\left(\frac{T}{\mu}\right)^{3/10} N[\text{Å}]$$
$$\Delta^{S,H}_{1/2} \approx 2.5 \times 10^{-9}\alpha_{1/2}N_e^{2/3}[\text{Å}]$$

Hydrogen-α Line Broadening:

- Neutral Broadening
- Doppler Broadening
- Resonance Broadening
- Van der Waals Broadening
- Stark Broadening

Table 3.3: Fractional Intensity Widths[48]

T (K)	T (eV)	N $(\#/m^3)$	$\alpha_{1/2}$
5000	0.431	1×10^{21}	9.69×10^{-3}
5000	0.431	1×10^{22}	14.9×10^{-3}
5000	0.431	1×10^{23}	18.9×10^{-3}
5000	0.431	1×10^{24}	N/A
5000	0.431	1×10^{25}	N/A
10000	0.862	1×10^{21}	7.77×10^{-3}
10000	0.862	1×10^{22}	13.4×10^{-3}
10000	0.862	1×10^{23}	18.6×10^{-3}
10000	0.862	1×10^{24}	21.5×10^{-3}
10000	0.862	1×10^{25}	N/A
20000	1.723	1×10^{21}	6.01×10^{-3}
20000	1.723	1×10^{22}	11.4×10^{-3}
20000	1.723	1×10^{23}	17.5×10^{-3}
20000	1.723	1×10^{24}	22.6×10^{-3}
20000	1.723	1×10^{25}	23.5×10^{-3}
30000	2.585	1×10^{21}	4.98×10^{-3}
30000	2.585	1×10^{22}	10.0×10^{-3}
30000	2.585	1×10^{23}	16.6×10^{-3}
30000	2.585	1×10^{24}	22.5×10^{-3}
30000	2.585	1×10^{25}	25.7×10^{-3}
40000	3.447	1×10^{21}	4.50×10^{-3}
40000	3.447	1×10^{22}	9.22×10^{-3}
40000	3.447	1×10^{23}	15.8×10^{-3}
40000	3.447	1×10^{24}	22.3×10^{-3}
40000	3.447	1×10^{25}	26.9×10^{-3}

Huddlestone & Leonard, *Plasma Diagnostic Techniques,* Academic Press, '65.

$$\Delta^{S,H}_{1/2} \approx 2.5 \times 10^{-9} \alpha_{1/2} N_e^{2/3} [\text{Å}]$$

Hydrogen-α Line Broadening:

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- Doppler Broadening
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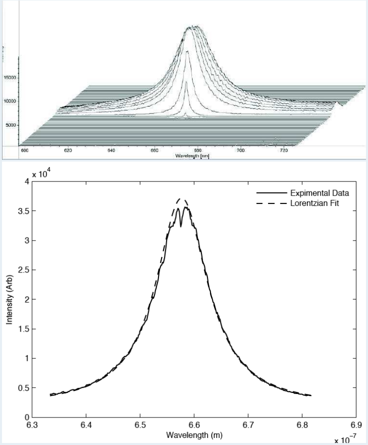
$$\Delta_{1/2}^{S,H} \approx 2.5 \times 10^{-9} \alpha_{1/2} N_e^{2/3} [\text{Å}]$$

Time Resolved Electron Density:

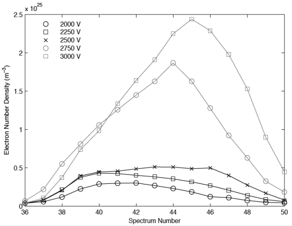
- Spectrum fit to Lorentzian Profile:
  $f(\lambda - \lambda_0) = \frac{1}{\pi\gamma}\left[\frac{\gamma^2}{\lambda^2+\gamma^2}\right]$ where 2γ=FWHM



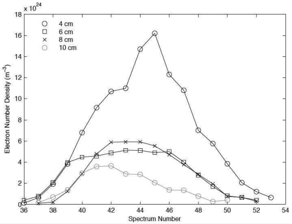
Pancotti, PhD Dissertation, USC, 2009.

Time Resolved Electron Density:

- Spectrum fit to Lorentzian Profile:
  $f(\lambda - \lambda_0) = \frac{1}{\pi\gamma}\left[\frac{\gamma^2}{\lambda^2+\gamma^2}\right]$ where 2γ=FWHM
- Fit inverted for n_e vs. Time
  - -Density $\rightarrow$ 1e25/m^3 Estimate
  - -Optical Depth $\rightarrow \approx$ Exit Plane n_e?



n_e vs. Time, 6cm Capillary



n_e vs. Time, 2500V Discharge

Pancotti, PhD Dissertation, USC, 2009.

0D Slab Model:

- Conservation of Mass:
$$V \cdot \frac{dn}{dt} = 2A_w \cdot \Gamma - A_e n^e C_s^e$$
- Conservation of Energy:
$$V \cdot \frac{d(n\epsilon)}{dt} = V \cdot \frac{I^2/A_e^2}{\sigma(n,T)} - A_e n^e C_s^e h - 2A_w \Theta$$

Where:

n is the Plasma/Gas Density
V is the Slab Volume
A_w is the Wall Area
A_e is the Exit Area
Γ is the Ablation Flux
C_s is Sound Speed (at the Exit)
Superscript-$()^e$ is Isentropically Expanded Exit Value

ϵ is the Energy Density
I is Current
$\sigma(n,T)$ is the Conductivity
h is the Enthalpy
C_s is the Sound Speed
Θ is the Wall Energy Flux

Pekker, 40th AIAA Plasmadynamics and Laser Conference, 2009.

0D Slab Model:

- Conservation of Mass:
  $$V \cdot \frac{dn}{dt} = 2A_w \cdot \Gamma - A_e n^e C_s^e$$
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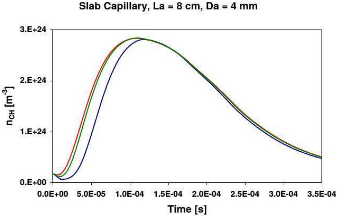

Fig. 6. Polyethylene number density in the plasma core region: blue - $\eta = 0.5$mm, green - $\eta = 0.1$mm, red - $\eta = 0.02$mm

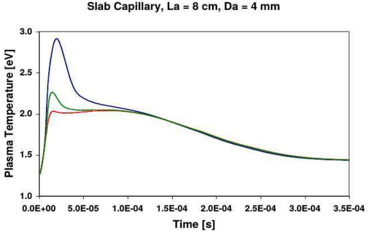

Fig. 8. Plasma temperature: blue - $\eta = 0.5$mm, green - $\eta = 0.1$mm, red - $\eta = 0.02$mm

Pekker, 40th AIAA Plasmadynamics and Laser Conference, 2009.

1D PDE Model:

- Conservation of Mass:
  $$\frac{\partial(A\rho)}{\partial t} + \frac{\partial}{\partial x}\left[(A\rho u)\right] = A_w \cdot \Gamma$$
- Conservation of Momentum:
  $$\frac{\partial(A\rho u)}{\partial t} + \frac{\partial}{\partial x}\left[(A(\rho u + p))\right] = p\frac{\partial A}{\partial x} - A_w f$$
- Conservation of Energy:
  $$\frac{\partial(Ae)}{\partial t} + \frac{\partial}{\partial x}\left[(Au(e+p))\right] = A\left(Q_j - Q_{rad} - Q_{conv} - Q_{ab} - \Phi\right)$$

Where:

A is the Cross Section Area

ρ is the Mass Density

u is the Velocity

A_w is the Wall Surface Area

Γ is the Ablation Mass Flux

p is the Pressure

f is the Viscous Wall Friction

e is the Total Energy

Q_j is the Joule Heating

Q_{rad} is the Radiant Energy Losses

Q_{conv} is the Convection Energy Losses

Q_{ab} is the Ablation Energy

Φ is Viscous Wall Energy Loss

Pancotti, PhD Dissertation, USC, 2009.

1D PDE Model:

- Conservation of Mass:
$$\frac{\partial(A\rho)}{\partial t} + \frac{\partial}{\partial x}\left[(A\rho u)\right] = A_w \cdot \Gamma$$
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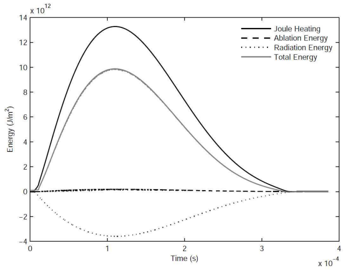
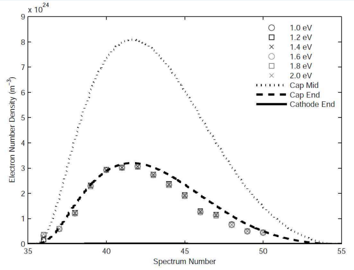
- Conservation of Energy:
$$\frac{\partial(Ae)}{\partial t} + \frac{\partial}{\partial x}\left[(Au(e + p))\right] = A\left(Q_j - Q_{rad} - Q_{conv} - Q_{ab} - \Phi\right)$$

Energy Flux for 5cm 2500V Capillary Discharge



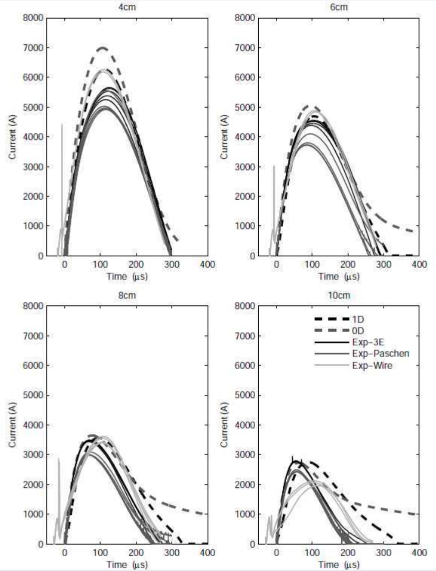
Comparison of 1D Model-n_e and Experimental Observation



Pancotti, PhD Dissertation, USC, 2009.

Discharge Current Predictions:

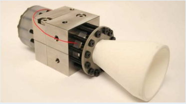
- Comparison of 2500V Discharge
- Similar Profiles/Trends
- Wire Highest Current
- Paschen Lowest Current
- Models Over-Predict Tail (Especially 0D)
- Initial dI/dt Incorrect



Pancotti, PhD Dissertation, USC, 2009.

For Proof-of-Concept Demonstration:

- Repeatable Ignition
  -3-Electrode System developed by Pancotti
- Desired Isp & η
  -Nozzle added for Efficient Energy Conversion
  -Additional Propellant Materials were Studied
  -High Efficiencies Demonstrated, Isp$\approx$1000s



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Additional Thruster Development

For Proof-of-Concept Demonstration:

- Repeatable Ignition

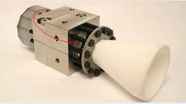
  -3-Electrode System developed by Pancotti

- Desired Isp & η

  -Nozzle added for Efficient Energy Conversion

  -Additional Propellant Materials were Studied

  -High Efficiencies Demonstrated, Isp$\approx$1000s



Tested Capillary Discharge Materials		
HDPE	PEEK	FEP
Nylon 6/6	Pyropel HD	PPS
Molybdenum Disulfied Nylon	Vespel	Delrin
Teflon	K-Fel	PTFE Delrin
Graphite Teflon	Rulon 123	POM
Fluorosint LF207	Rulon 142	Acetal Copolymer
Fluorosint HPV	Torlon	Turcite
	Radel	PVFD

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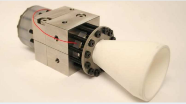
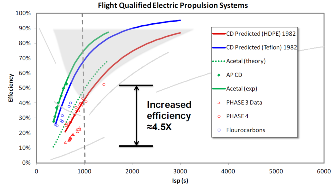


Tested Capillary Discharge Materials		
• HDPE	• PEEK	• FEP
• Nylon 6/6	• Pyropel HD	• PPS
• Molybdenum Disulfied Nylon	• Vespel	• Delrin
• Teflon	• K-Fel	• PTFE Delrin
• Graphite Teflon	• Rulon 123	• POM
• Fluorosint LF207	• Rulon 142	• Acetal Copolymer
• Fluorosint HPV	• Torlon	• Turcite
	• Radel	• PVFD



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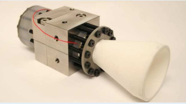
For Proof-of-Concept Demonstration:

- Repeatable Ignition
  - -3-Electrode System developed by Pancotti
- Desired Isp & η
  - -Nozzle added for Efficient Energy Conversion
  - -Additional Propellant Materials were Studied
  - -High Efficiencies Demonstrated, Isp$\approx$1000s
- Robust Propellant feed Mechanism
  - -Remains Unresolved
  - -Burton studied Liquid/Gas Schemes
  - -Additional research Required



Tested Capillary Discharge Materials		
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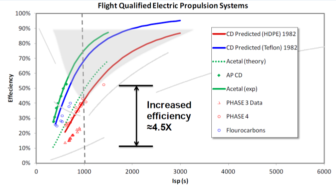

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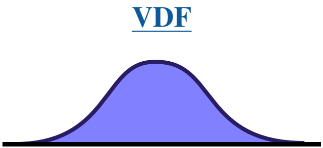
Breakdown non-LTE:

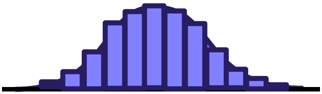
- Many Particles →≈Continuous Distribution



Breakdown non-LTE:

- Many Particles →≈Continuous Distribution
- Discretized VDF yields Vlasov Models
  But 3D3V Severe Dimensionality Curse

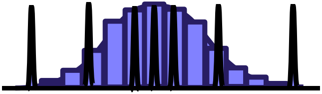
VDF



Breakdown non-LTE:

- Many Particles →≈Continuous Distribution
- Discretized VDF yields Vlasov Models
  But 3D3V Severe Dimensionality Curse
- Particle Methods (i.e. PIC) Simplify to Delta Functions
- Sparse Representation in 3D3V Phase Space
  But Added Noise and Low Dynamic Range

VDF



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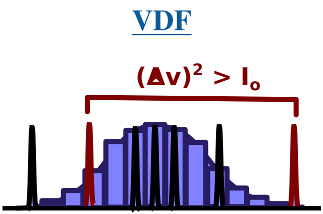
- Collisions between Discrete Velocities
- Inelastic Collisions in Tail Impact High Moments



Breakdown non-LTE:

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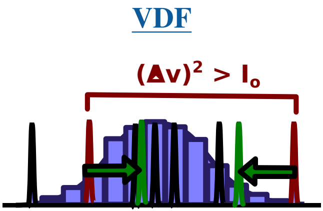
- All-or-Nothing Collision $\rightarrow$ Rare Large Events



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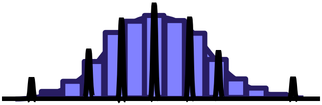
- All-or-Nothing Collision $\rightarrow$ Rare Large Events
- Variable Weights $\rightarrow$ more DOF representing Tails

VDF



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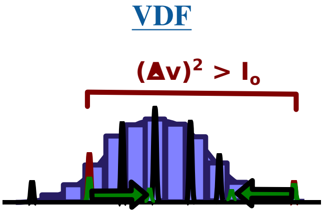
- Collisions between Discrete Velocities
- Inelastic Collisions in Tail Impact High Moments
- All-or-Nothing Collision $\rightarrow$ Rare Large Events
- Variable Weights $\rightarrow$ more DOF representing Tails
- Fractional Collisions $\rightarrow$ New Numerical Particles



Breakdown non-LTE:

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  But 3D3V Severe Dimensionality Curse
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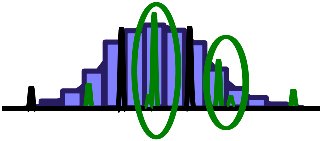
- Sparse Representation in 3D3V Phase Space
  But Added Noise and Low Dynamic Range
- Collisions between Discrete Velocities
- Inelastic Collisions in Tail Impact High Moments
- All-or-Nothing Collision → Rare Large Events
- Variable Weights → more DOF representing Tails
- Fractional Collisions → New Numerical Particles
- Conservative Merge Needed to Control Growth

VDF



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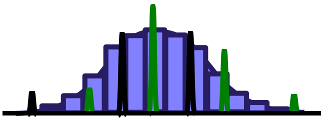
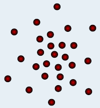
VDF



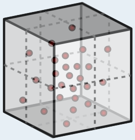
Phase-Space Decomposition

- Given a Set of Particles...



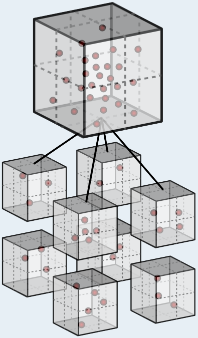
Phase-Space Decomposition

- Given a Set of Particles...
- Particles Binned in Octants



Phase-Space Decomposition

- Given a Set of Particles...
- Particles Binned in Octants
- Octants Recursively Sub-Divided

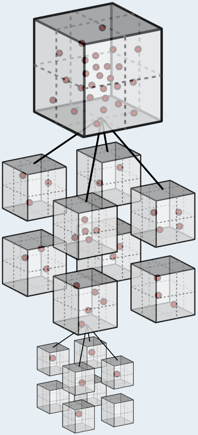


Phase-Space Decomposition

- Given a Set of Particles...
- Particles Binned in Octants
- Octants Recursively Sub-Divided
- Recursion Halted at 1-Particle/Bin or Other Criteria such as Bin-Density

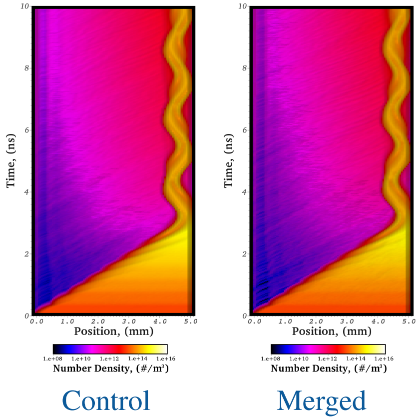
Restricts Phase-Space Diffusion to Within Local Bins

(Entropy, $\sum n\ log(n)$, Constant within Octree Adaptive Quadrature)



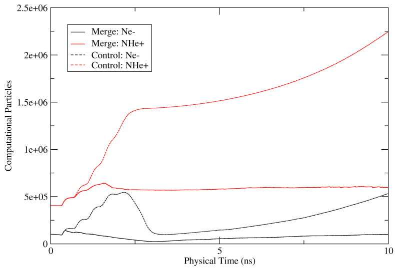
250V DC-Diode Test Case:

- Full 3D Electrostatic-PIC
- Averaged to 1D XT-Plot
- 250V Cathode → Anode
- MCC-Ionization Collisions
- Secondary Emission at Cathode



250V DC-Diode Test Case:

- Full 3D Electrostatic-PIC
- Averaged to 1D XT-Plot
- 250V Cathode → Anode
- MCC-Ionization Collisions
- Secondary Emission at Cathode
- Weak Chain-Branching (Marginal on Paschen Curve)



250V DC-Diode Test Case:

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- 250V Cathode $\rightarrow$ Anode
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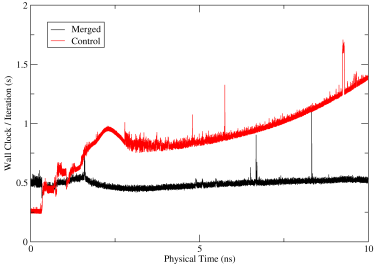
- Secondary Emission at Cathode
- Weak Chain-Branching (Marginal on Paschen Curve)
- Negligible Merge Overhead



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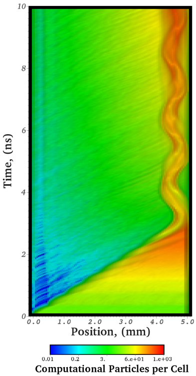
- Secondary Emission at Cathode
- Weak Chain-Branching (Marginal on Paschen Curve)
- Negligible Merge Overhead
- Control: Parts/Cell $\propto$ Density



Control Merged

250V DC-Diode Test Case:

- Full 3D Electrostatic-PIC
- Averaged to 1D XT-Plot
- 250V Cathode $\rightarrow$ Anode
- MCC-Ionization Collisions
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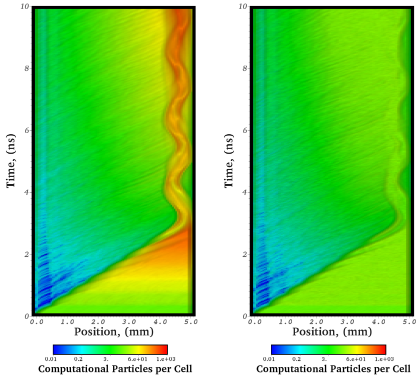
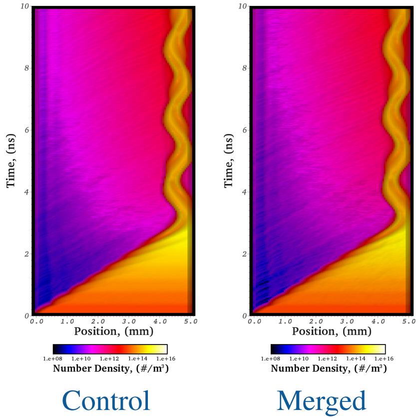
- Weak Chain-Branching (Marginal on Paschen Curve)
- Negligible Merge Overhead
- Control: Parts/Cell $\propto$ Density
- Merge: Parts/Cell **Reduced**



Control Merged

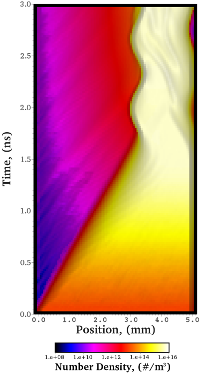
250V DC-Diode Test Case:

- Full 3D Electrostatic-PIC
- Averaged to 1D XT-Plot
- 250V Cathode → Anode
- MCC-Ionization Collisions
- Secondary Emission at Cathode
- Weak Chain-Branching (Marginal on Paschen Curve)
- Negligible Merge Overhead
- Control: Parts/Cell $\propto$ Density
- Merge: Parts/Cell **Reduced**
- Despite Identical Densities



1KV DC-Diode Test Case:

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization



Control

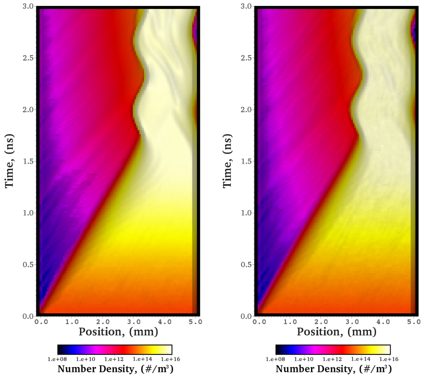
Merged

Martin, Cambier, JCP, (accepted), 2016.

(doi:10.1016/j.jcp.2016.01.020)

<u>1KV DC-Diode Test Case:</u>

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization
- Major Features Captured



Control

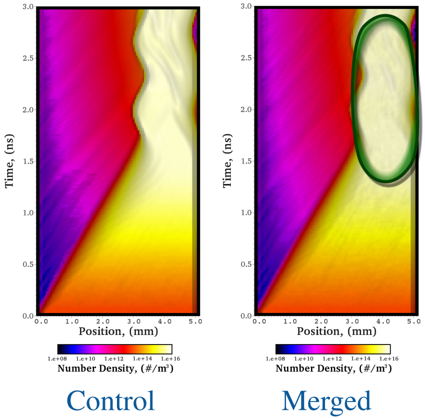
Merged

Martin, Cambier, JCP, (accepted), 2016.

(doi:10.1016/j.jcp.2016.01.020)

<u>1KV DC-Diode Test Case:</u>

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization
- Major Features Captured
- Some Features Lost...



Martin, Cambier, JCP, (accepted), 2016.

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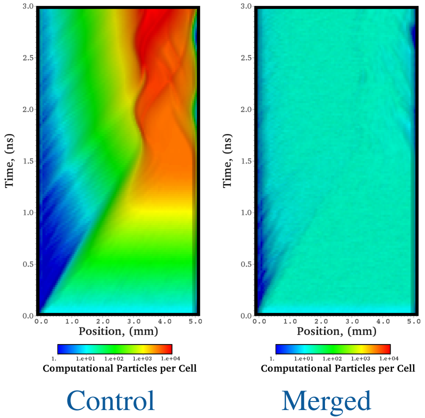
1KV DC-Diode Test Case:

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization
- Major Features Captured
- Some Features Lost...
- Might be Captured by Increasing Target #/cell?



Martin, Cambier, JCP, (accepted), 2016.

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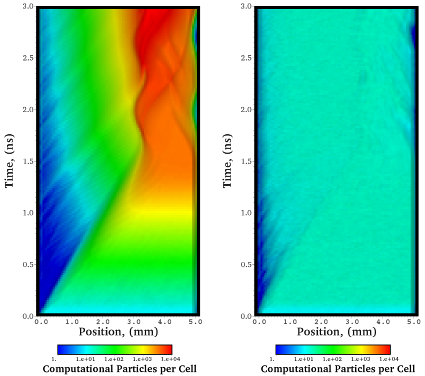
1KV DC-Diode Test Case:

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization
- Major Features Captured
- Some Features Lost...
- Might be Captured by Increasing Target #/cell?
- 26x Speedup



Control Run: 6hr12min

Merged Run:14min

Martin, Cambier, JCP, (accepted), 2016.

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1KV DC-Diode Test Case:

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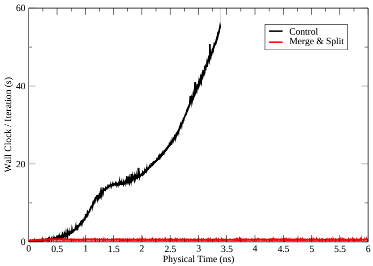
- Major Features Captured
- Some Features Lost...
- Might be Captured by Increasing Target #/cell?
- 26x Speedup
- Control Halted Mem>15GB



Martin, Cambier, JCP, (accepted), 2016.

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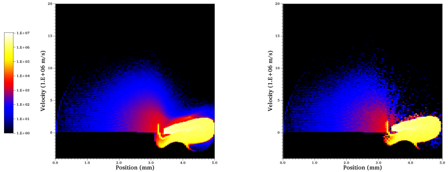
1KV DC-Diode Test Case:

- Voltage increased to 1KV
- Otherwise Identical to 250V
- Much Stronger Ionization
- Major Features Captured
- Some Features Lost...
- Might be Captured by Increasing Target #/cell?
- 26x Speedup
- Control Halted Mem>15GB
- Major VDF Features Captured
- Future? Hybrid Kinetic/Fluid

Control Merged



VDFs at 3ns

Martin, Cambier, JCP, (accepted), 2016.

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Thank You

This Presentation is derived from Anthony Pancotti's Dissertation Work:

A Study of Ignition Effects on Thruster Performance of a Multi-Electrode Capillary Discharge using Visible Emission Spectroscopy Diagnostics

(http://digitallibrary.usc.edu/cdm/ref/collection/p15799coll127/id/270907)

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Questions?